Progress Report: Effects of Small-Scale Bathymetric Roughness on the Global Internal Wave Field

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LONG-TERM GOALS

The small-scale roughness properties of the seafloor are increasingly being recognized as critical parameters in determining important processes in physical oceanography. For instance, *in situ* observations (e.g., Polzin et al., 1997) find that mixing levels are greatly elevated in regions of rough topography. Gille et al. (2000) demonstrate that mesoscale eddy energy tends to be lower in areas where the bottom is rough (suggesting that substantial dissipation of eddy energy takes place in such areas), and Egbert and Ray (2003) show that substantial tidal dissipation occurs in such areas. The dissipation is generally thought to arise from the breaking of internal waves generated by flows over the rough seafloor. On the time scales of internal waves, mesoscale eddies and the general circulation can be regarded as steady, while tides are oscillatory. The physics of linear internal wave generation is different for these two classes of motions (e.g., Bell 1975), but for both types of flows the wave generation is strongly dependent on the horizontal and vertical scales inherent in the bottom topography. Using the classical formulation for lee waves (e.g., Cushman-Roisin, 1994, St. Laurent, 1999), one can argue that horizontal wavelengths ranging from ~60 m to 6 km generate internal waves when forced by steady flows. Features typical of abyssal hill morphology (e.g., 50 m height over 1 km horizontal scale) will generate a significant vertical internal wave energy flux. Topographic information on scales of order 1 km is also important for internal tides. Carter et al. (2008) showed that 1 km horizontal resolution in a regional internal tide model results in 20% higher barotropic-to-baroclinic conversion than found in a model with 4 km resolution. Non-linear effects may be important as well, as some oceanographers (e.g., Thurnherr and Richards, 2001; Thurnherr et al., 2002; Thurnherr and Speer, 2003; St. Laurent and Thurherr, 2007) have argued from observational data that

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turbulence associated with hydraulic jumps occurs in area of rough topography when the Froude number Nh/U exceeds an order one threshold. For typical abyssal values of the Brunt-Vaisala frequency N and velocity U (10^{-3} s^{-1} and 10^{-2} m s^{-1}, respectively) this occurs when topography h over scales of 1 km exceeds about 10 m in height, which is typically the case for abyssal hill morphology.

A significant dilemma for physical oceanographers studying these processes is that the kind of bathymetric resolution required to model these processes over entire ocean basins are not available, nor will be any time soon. Acoustic bathymetric data, which can achieve lateral resolutions of 0.1-0.2 km, presently cover only a few percent of the ocean floor beyond the exclusive economic zones in coastal areas. A complete swath survey of all the deep oceans would take ~200 years of ship time at a cost of billions of dollars (Carron et al., 2001). The most comprehensive determination of bathymetry world-wide is the Smith and Sandwell (1994; 1997; 2004) model derived from satellite altimetry data combined with data from ship soundings, but the resolution of this product is limited to >10 km in the deep ocean. We seek to resolve this dilemma through a statistical modeling approach that globally predicts abyssal hill roughness properties based on paleo-spreading rates and directions, with modification by existing sediment cover (Goff and Arbic, 2009).

Numerical modeling of physical oceanographic processes, either at regional or global scales, requires adequate knowledge of the bathymetry at the model resolution scale. Although basin-wide or global determination of true bathymetry at abyssal hill scales is not feasible, we can create any number of synthetic realizations at arbitrary resolution that matches the statistical prediction. We have created such realizations (Goff and Arbic, 2009), and propose that they can be used as an overlay on the overly-smooth global bathymetric models (Smith and Sandwell, 1997; 2004) to provide realistic small-scale roughness texture for modeling purposes.

We are addressing issues of importance to the Navy with tide models that utilize this information, either by directly resolving internal wave generation over the rough seafloor, or by parameterizing the dissipation of these internal waves. In particular, we have shown that introduction of the statistical roughness into a global internal tide model increases the resolved internal wave activity in the model. We will shortly be investigating how the statistical roughness affects the parameterizations of drag and energy loss due to unresolved breaking internal waves in global tide models. Schemes in use in some tide models (e.g., Arbic et al., 2004) utilize a “multiplicative factor” which is argued to account for the lack of small scales in the topographic datasets. It is expected that usage of the statistical roughness will allow for a decrease in this multiplicative factor, thus providing for a more satisfying wave drag parameterization. This parameterization is used in the operational Navy models that Arbic is also working on with Eric Chassignet of Florida State University and several collaborators at the Stennis Space Center branch of the Naval Research Laboratory. Finally, the statistical roughness product provides leverage for two recently submitted National Science Foundation proposals which Arbic is involved in. One proposed project will examine the loss of energy of the low-frequency eddying general circulation due to internal wave drag over rough topography. The other proposed effort, led by Jennifer MacKinnon of the Scripps Institution of Oceanography, will be a comprehensive study of mixing parameterizations in ocean models.

OBJECTIVES

Our main objectives are to characterize seafloor roughness statistically and to investigate the impact of rough topography on the global internal wave field. Specific tasks are to:

(1) Generate maps of abyssal hill roughness parameters across the ocean basins.

(2) Generate synthetic topography for use in global models.

(3) Determine how to enter the roughness into the bathymetry maps used in global models in a smooth way.

(4) Determine the increase in internal wave activity in global baroclinic tide models due to the added roughness.

(5) Determine the impact of the added roughness on parameterizations of unresolved topographic wave drag in global tide models. (Planned work by Arbic in collaboration with HYCOM team at Stennis Naval Research Laboratory.)

(6) Determine the impact of the added roughness on parameterizations of unresolved topographic wave drag in global models of low-frequency motions.

(7) Determine the impact of the added roughness on mixing parameterizations used in global internal internal wave models and in climate models.

APPROACH

For objective (1)—generation of roughness parameter maps. Abyssal hill statistical properties are modeled using the von Karman statistical model (Goff and Jordan, 1988), which parameterizes rms heights, characteristic lengths and widths, strike orientation and fractal dimension. Predictions for unsedimented abyssal hill statistical properties are derived from a summary by Goff et al. (1997) of average von Karman parameter values as a function of spreading rate, which were estimated using relationships developed by Webb and Jordan (2001) based on application of a diffusion model over rough surfaces. Goff and Arbic (2009) presents a global prediction of abyssal hill roughness parameters based on available maps of paleo-spreading properties (Muller et al 2008) and sediment thickness (National Geophysical Data Center; http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html).

For objective (2)—generation of synthetic topography. A spectral method for generating synthetic topography from the von Karman statistical model was introduced by Goff and Jordan (1988). However, spectral methods require homogeneity of statistical properties throughout the simulation grid, and so are unsuitable for these purposes because abyssal hill properties will change significantly over the regional or global scales. We solve this problem by utilizing a spatial filter, whose characteristics vary with location, applied to an uncorrelated random field. Although computationally less efficient than the spectral method, this spatial filter method provides the flexibility required to simulate inhomogeneous fields.

For objective (3)—entering roughness into bathymetries used in global models. Building upon work by Arbic et al. (2009), we are using 1/12° HYCOM as a global tide model. The new bathymetry for the tide model is derived by combining the latest Smith and Sandwell (1997) bathymetric database (SS) together with an empirically derived estimate of abyssal hill roughness as described above. Both products are provided at a resolution of 30 arc seconds. The SS data has been interpolated onto the 1/12° HYCOM grid using a Blackman filter with radius R=10 km. The SS bathymetry also includes a parameter (SID) to identify the source of actual sounding data used in the preparation of the bathymetric data. We convert this parameter to a field of 0’s and 1’s to indicate that the bathymetry is measured (SID = 1) or estimated from altimetry (SID = 0). The Goff

roughness prediction (G) is an empirically derived estimate of bottom roughness for the World Ocean. If the SS data is derived from actual soundings then we do not wish to alter the bathymetry by adding a roughness parameter. Therefore, in order to add the Goff roughness field which resolves abyssal hill roughness on horizontal scales of order 2-10 km, we calculate a weight $\alpha(x,y)$ for each ordinate pair on the 30 arc second grid. α is a filtered version of the 0 and 1 field, filtered in the same manner as the HYCOM model bathymetry but with a smaller filter radius R = 5 km. We produce a new bathymetry h_SS_G(x'y') on a 30 arc second grid using:

$$h\_SS\_G(x',y') = SS(x',y') + (1 - \alpha) * G(x',y').$$

For objective (4)—determining the increase in modeled wave activity due to the added roughness. Patrick Timko, a postdoc partially employed by the ONR grant, has run HYCOM as a global internal tide model with 16 isopycnal layers, both with and without the added roughness. The stratification is horizontally uniform, as in earlier global baroclinic tide models (Arbic et al., 2004; Simmons et al., 2004), and is based on the subtropical stratification seen in WOCE line P15. The model is initialized from rest and forced with the five largest tidal constituents, M_2, S_2, N_2, K_1, and O_1. The simulation was run for 60 days, and only the last 30 days were analyzed (to allow for spinup). The errors of the sea surface elevations with respect to a standard set of 102 pelagic tide gauges (Shum et al. 1997) are comparable to those seen in other carefully tuned forward tide models (e.g. Arbic et al. 2004). We examine the increase in internal wave activity as a result of the added roughness.

For objective (5) —determining the impact of the added roughness on parameterizations of unresolved topographic wave drag in global tide models. In separately funded work, Arbic has collaborated with Eric Chassignet at FSU and several scientists at NRL Stennis Space Center to embed tides (both barotropic and baroclinic) into the 1/12° HYCOM eddying general circulation model that is being groomed for use as the next-generation US Navy ocean forecast model. As in Arbic et al. (2004), and the work done by Timko described above, this model utilizes a parameterized topographic wave drag acting on the bottom layer flow. This drag is thought to represent drag due to unresolved breaking of high mode baroclinic tides, and is necessary to ensure an accurate barotropic tide in baroclinic models (see discussions in Arbic et al. 2004, 2009). The drag is based upon the scheme of Garner (2005), which comes from the atmospheric literature, but a “multiplicative factor” of about 6 must be used for the barotropic tides to be accurate. We would like to have a wave drag scheme which does not require such a large multiplicative factor to be entered into the parameterization. Arbic et al. (2004) speculated that the multiplicative factor may be necessary to make up for the lack of small scales in available global bathymetric datasets. We will shortly use the statistical roughness together with the Garner (2005) parameterization to determine whether the addition of the Goff and Arbic (2009) small-scale roughness enables accurate barotropic tides with a smaller multiplicative factor. If successful, this endeavor will lead to a drag scheme which is more philosophically satisfying. The approach for objectives (6) and (7) will be described in the “RELATED PROJECTS” section.

WORK COMPLETED

Objectives (1) and (2) have been completed. We have generated maps of abyssal hill roughness parameters across the ocean basins, and used them to generate synthetic topography for use in global models. The results of this completed work in Goff and Arbic (2009). Objective (3) has also been completed. Patrick Timko, a postdoc working with Arbic, has entered the synthetic roughness map produced in Goff and Arbic (2009; objective 2) into the bathymetry maps used in 1/12° global

HYCOM. Timko is also working on objective (4), the determination of the increase in internal wave activity in global HYCOM (run as a global baroclinic tide model) due to the added roughness.

Arbic plans to soon undertake work related to objective (5), the determination of the impact of the added roughness on parameterizations of unresolved topographic wave drag in global tide models, in collaboration with the HYCOM team at the Stennis Space Center branch of the Naval Research Laboratory. Objectives (6) and (7) are related to two recently submitted NSF proposals which Arbic is involved in, described in the "RELATED PROJECTS" section.

RESULTS

First we show two results from Goff and Arbic (2009), which describes the generation of maps of abyssal hill roughness parameters and the generation of synthetic topographies. Fig. 1 shows the globally predicted abyssal hill rms heights (Goff and Arbic, 2009). Fig. 2 shows synthetic roughness in the North Atlantic sector of a global realization done at 30 arc seconds resolution, derived from the procedure described above.

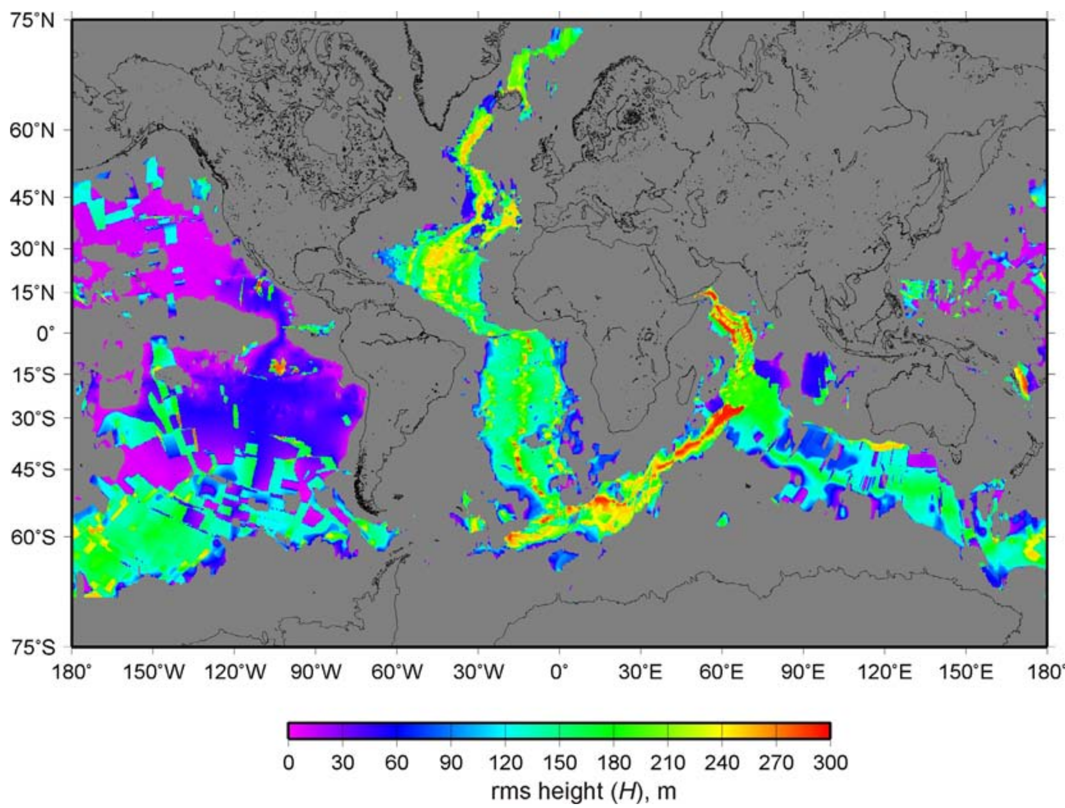

Figure 1. Global predicted abyssal hill rms heights. Gray areas indicate regions of no predicted abyssal hill roughness due to sediment cover.

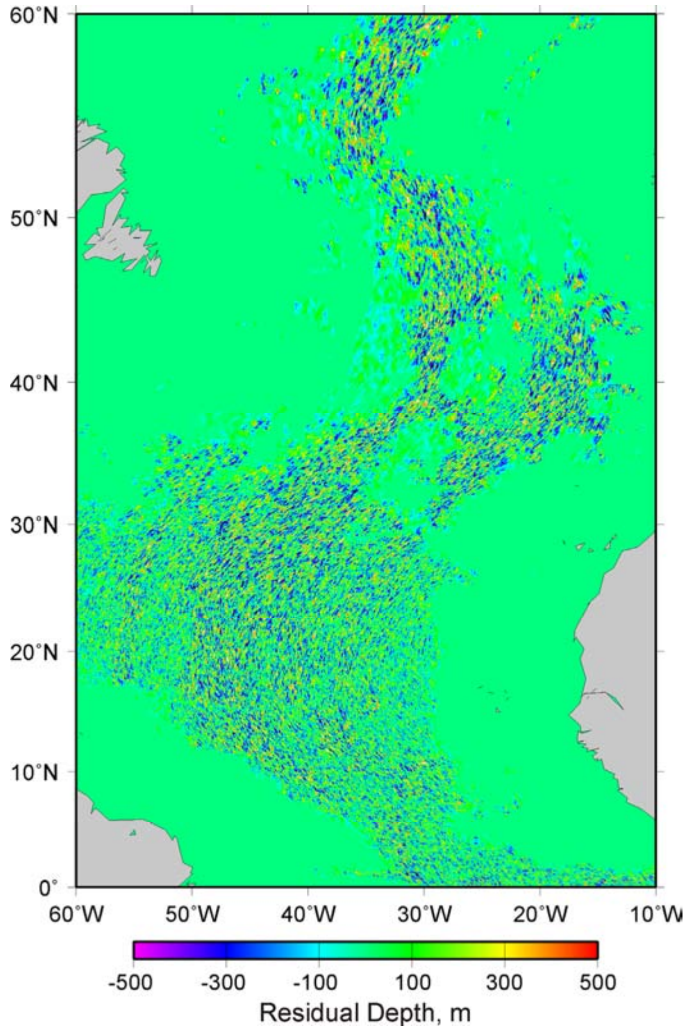

Figure 2. Synthetic realization of abyssal hill topography in the North Atlantic Ocean based on predicted statistical parameters.

Next we show results from Timko's work on inserting the roughness into the 1/12° HYCOM grid, and determining the difference the added roughness makes to the modeled global internal tide field. Fig. 3 shows the added roughness after the statistical product has been filtered onto the 1/12° HYCOM grid. Because the grid spacing at 1/12° resolution is comparable to the horizontal length scales of abyssal hills, much of the abyssal hill roughness has been smoothed out at this resolution. The added roughness is greater when filtered onto a 1/25° HYCOM grid.

Preliminary results in the HYCOM baroclinic tide model show an increase in the rms interfacial displacements over all but 9 of the 80 interfaces that we examined (16 interfaces in each of 5 representative regions). In most regions, increases in rms values are typically relatively small; about 1%-6%. Fig. 4 shows the rms interfacial displacements as a function of depth, averaged over the three regions outlined in boxes in Fig. 3. The roughness leads to larger internal waves in the Atlantic, but interestingly makes an even larger difference in the South Pacific, where the local roughness is not significantly enhanced. Nonlocal effects therefore seem to be important; this is the subject of continued investigation. Because the difference in roughness with the statistical topography added in

is much larger at 1/25° resolution than at 1/12° resolution, we anticipate that experiments run at 1/25° resolution will show a greater difference in the interfacial displacements with the addition of the synthetic roughness. Preparations for these 1/25° experiments are underway, and they will be conducted shortly.

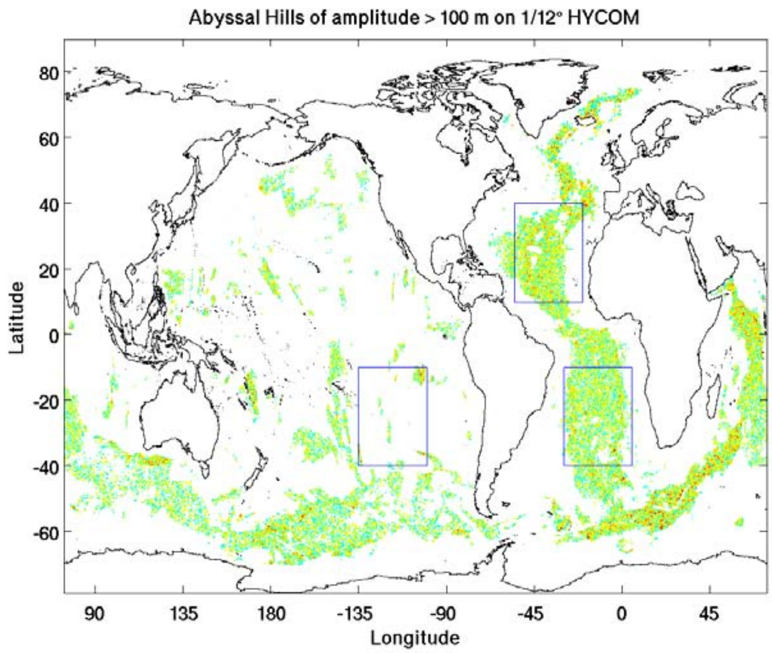

Figure 3. Abyssal hills on 1/12° HYCOM grid. Shown are amplitudes of +/- 100 m to +/- 600 m, at 100 m intervals.

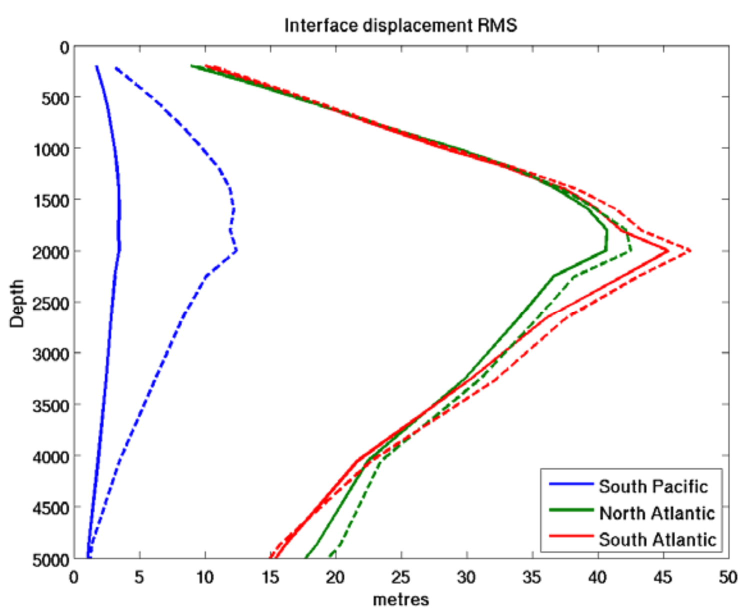

Figure 4. RMS (m) of the interface displacements. Dashed lines represent results from the model runs after statistical roughness has been added.

IMPACT/APPLICATIONS

Synthetic, predictive maps of small-scale seafloor roughness can be used to realistically "roughen" lower-resolution global bathymetry maps, which can then be incorporated into oceanographic modeling efforts to predict critical phenomena such as the generation of internal waves and mixing by both tidal and non-tidal (i.e., mesoscale eddy) flows. As computing power increases, the resolution of numerical ocean models has begun to outstrip the actual resolution of the available topographic databases, hence the need for the statistical product described here.

RELATED PROJECTS

Collaboration with NRL to insert tides into HYCOM eddying general circulation runs Arbic has had a separate contract with the Stennis branch of the Naval Research Laboratory to implement global tides in HYCOM, the next-generation Navy operational global model, and is currently writing a NOPP proposal to enable a continuation of this work. Arbic has developed a good working relationship with several of the key HYCOM investigators (e.g. Alan Wallcraft, Joe Metzger, Harley Hurlbert, Jim Richman, Jay Shriver, and others). Wallcraft and Arbic implemented tides into HYCOM, and Wallcraft and Metzger recently completed a 5-year run of the global 1/12° model with tides (Arbic et al., 2009). Preliminary results already indicate important impacts of the tides on the ocean general circulation, and several analyses and further improvements to the model are planned. As described above, the parameterization of topographic wave drag on both tidal and non-tidal motions in HYCOM is expected to be enhanced by the bathymetric roughness work done in the current project. In addition, postdoc Patrick Timko, working with Arbic, has learned to run and analyze HYCOM tidal simulations, as well as to constuct bathymetric grids for use in HYCOM. Timko will continue to work on both Navy-funded projects, thus benefitting both projects greatly.

Related NSF proposal submissions Arbic has been lead PI on one recently submitted NSF proposal which will benefit from the work done here, and co-PI on another. The former includes plans to insert topographic wave drag into models of the eddying general circulation, to examine whether wave drag is a major player in the energy budget of such motions, as suggested by Naveira-Garabato et al. (2004) and Nikurashin (2008). The small-scale statistical roughness will be especially valuable in this study, since, as noted by St. Laurent (1999), topography having horizontal scales of order 1 km are implicated in the generation of internal waves by low frequency flows. The project on which Arbic is co-PI is a Climate Process Team (CPT) proposal led by Jennifer MacKinnon of Scripps. The focus of the project is on understanding and parameterizing internal wave driven mixing in ocean models. Global internal wave simulations will be performed with both the Hallberg Isopycnal Model, as in Arbic et al. (2004) and Simmons et al. (2004), and with HYCOM, as in Arbic et al. (2009). Arbic and other collaborating PIs will be involved in simulations with both models. We anticipate using the Goff and Arbic (2009) topography in this project as well since it should enhance the internal wave fields in presumably realistic ways.

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